Towards Micropropulsion Systems on-a-Chip: Initial Results of Component Feasibility Studies

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Abstract -- Recent advances in the development of several micropropulsion components performed at JPL for microspacecraft applications are reported upon. These include a vaporizing liquid micro-thruster, a micro ion engine, a micro-isolation valve, and a micro solenoid valve. The latter is being developed in collaboratio with Moog Space Products Division. These components are envisioned to be integrated with chip-based driver and power conditioning electronics into highly integrated, compactly configured micropropulsion modules, reducing overall system weight and size and reducing the cost and complexity of propulsion system integration into a microspacecraft bus. The micropropulsion concepts studied are in various stages of their development. Proof-of-concept demonstration for several of the concepts were recently obtained. A vaporizing liquid thruster chip was able to demonstrate vaporization of water propellant at a power level of 2 W. A micro-isolation valve could be opened at an energy of 16 mJ within 0.1 ms, and sustain burst pressures of up to 3,000 psig, despite being manufactured entirely from silicon and Pyrex.

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1. INTRODUCTION

Microspacecraft are gaining increasing attention within the aerospace community. Within the National Aeronautics and Space Administration (NASA), a constellation of consisting of 10-kg microspacecraft has been selected as the New Millennium ST-5 mission designed to map Earth's magnetic field [1]. The Air Force is studying a constellation consisting of thirty-five 100-kg spacecraft to demonstrate the feasibility of distributed space systems to perform radar observations of objects on Earth [2]. A joint Air Force Office of Scientific Research (AFOSR)/Defense Advanced Research Projects Agency (DARPA)/NASA Goddard program supports ten university "nanosatellite" projects designed to demonstrate the feasibility of developing and flying 10-kg microspacecraft. Several of these projects are interrelated and also focus on formation flying missions [3].

The aforementioned examples demonstrate one of the current main motivators for exploring microspacecraft technologies, namely the ability to fly distributed space systems consisting of multiple small spacecraft. Such mission architectures are pursued, for example, to either increase the scientific return of a mission (simultaneous "tensor" mapping of field and particles at a multitude of locations [4]), to achieve increased resolution with a distributed antenna array, or to ensure increased survivability of space assets in both military and civil application. Loss of a single microspacecraft may decrease the performance of the constellation, but may not endanger the mission.

Large constellations consisting of conventionally sized spacecraft, however, would be very costly to build and launch and, thus, such mission scenarios may greatly benefit from a miniaturization of spacecraft. Other potential applications for microspacecraft have been proposed, such as the use of these craft to serve as probes to undertake particularly dangerous portions of a mission, i.e. a close-up exploration of Saturn's rings [5] , for example, to be launched from larger craft staying safely behind, or even human-tended missions, using microspacecraft to inspect a space station, or other satellites. More generically, the use of microspacecraft will reduce launch cost, and allow for more frequent launches and missions within a given budget.

Microspacecraft will require substantial development efforts to achieve miniaturization of subsystems, not only with respect to size and weight, but also with respect to power. In addition, bus voltages available on these craft may also be substantially lower (in the $\leq$ 5 V range) than for conventional craft. One of the subsystems impacted by the need for miniaturization is propulsion. Miniaturization requirements will vary depending on what spacecraft size/mass range is being targeted. A large range of masses and szes for microspacecraft is currently being considered, and spacecraft have been classified differently with respect to mass and size. A summary of some of these definitions and resulting propuliosn requirements for each microspacecraft category is given in Table 1 [6].

The propulsion system requirements are approximate at this stage of microspacecraft development. Roughly, larger craft (100-kg class) may very well be ale to still use existing propulsion technologies, possibly relying on increasngly lighter weight components as they become available. However, the need to develop new technologies and novel integration schemes increases towards the lower mass range considered in Table 1, i.e. below approximately 5-20 kg total spacecraft mass. New miniaturized components will be needed for this class of spacecraft, although they may still be integrated using conventional means, i.e. using welded tube joints. One example of a demonstrator of such a craft is shown in Fig. 1. This craft, termed the "2nd Generation Microspacecraft" and developed at the Jet Propulsion Laboratory (JPL) [7], has a mass of around 7-8 kg in its current design iteration. In this spacecraft design, propellant feed lines also serve as the spacecraft bus structure. Note that the "2nd Generation Microspacecraft" is not designed for flight, but, rather, it is an evolutionary functional model of such a craft, with subsystem hardware constantly being upgraded to more "flight-like" versions.

For even smaller spacecraft designs more radical design innovations will be required. Here, the use of relatively novel microfabrication, or MEMS (Microelectromechanical Systems), technologies may need to be exploited. This fabrication technology, typically based

Table 1: Definitions and Classifications of Microspacecraft

Designation	S/C Mass (kg)	S/C Power (W)	S/C Dimension (m)	Comments
"Microspacecraft" (AF/European Definition)	10-100	10-100	0.3-2	Micropropulsion concepts beneficial due to weight/size savings, possibly enabling based on performance requirements (e.g. very small impulse bits for ultra-fine spacecraft pointing). Low end of mass range - see below.
"Class I Microspacecraft" (<10 kg: "Nanosat")	5-20	5-20	0.2-0.4	Use miniature "conventional" components, possibly MEMS/micro-fabricated. Conventional integration (e.g. feed lines) still possible, higher level of integration between components/subsystem desirable.
"Class II Microspacecraft" ("Nanosat")	1-5	1-5	0.1-0.2	MEMS/microfabricated components, high level of integration between components and subsystems required (subsystems on a chip?)
"Class III Microspacecraft" ("Picosat")	<1	<1	<0.1	All MEMS/microfabricated. Very high level of integration between all subsystems and within subsystems required. Strong feasibility issues for masses substantially less than 1 kg at this time. Not considered in this study.

Fig. 1: JPL "Second Generation Microspacecraft"

on the chemical manipulation (etching, deposition) of silicon wafer substrates, allows for the fabrication of extremely small devices with feature tolerance of 1 μm or less. Such technologies have been successfully applied in the development of microsensors, some of which have been brought to flight, however, adaptation of this fabrication technology to propulsion systems and components is at present only in its earliest stages.

This paper will review some of the ongoing work in this new field of micropropulsion research, and discuss some of the design concepts studied at JPL in greater detail. While none of the projects currently undertaken are ready for flight in the near term, they illustrate the potential of a significant degree of miniaturization and integration between components that may be achievable in the not too distant future.

2. MEMS MICROPROPULSION - AN OVERVIEW

Motivation for Exploring MEMS Propulsion Systems

Reasons for exploring MEMS technologies in the fabrication of micropropulsion components and systems may roughly be related to (1) size, (2) performance, and (3) integration. The first item is the most obvious. Using MEMS technology, very small features may be fabricated to extremely tight tolerance (1 μm or less), allowing overall device size to be reduced significantly. In particular for very small microspacecraft (Class II in Table 1), the ability to fabricate very small and light-weight devices becomes increasingly important.

Performance characteristics may also be an important factor. Exploiting the ability to fabricate extremely small feature sizes to tight tolerances using MEMS technologies, very small nozzle throat diameters can be manufactures, reducing thrust level and potentially impulse bits (thrust integrated over thruster on-time) achievable with MEMS-based propulsion devices. It has been estimated that impulse bit requirements may range into the micro-Newton-sec range for very small (Class II) microspacecraft, depending, obviously, on the required pointing accuracy and thus the particular mission chosen [6]. Conventional, low impulse bit cold gas thruster technology typically delivers around 10^{-4} Ns at present [6].

Finally, using MEMS technology much higher levels of integration may be achieved between propulsion components as well as their driver and power conditioning electronics. This is illustrated in Fig. 2. Conventional feed systems, as indicated in the left hand side of Fig. 2, consist of components interconnected by weld joint tubing. Recently, some components have undergone dramatic reduction in size and mass, as indicated in the center picture of Fig. 2, showing the example of a miniature cold gas solenoid valve manufactured by the Moog Company. However, even these components still require conventional (i.e. tube weld joint) integration. As spacecraft get smaller, facilitating this type of integration within ever decreasing spacecraft envelopes becomes increasingly complex. Smaller tube diameters and new joining technologies may have to be explored, and the available degree of miniaturization for the entire system may be limited as each component is packaged individually and space will be needed between components to establish the tube joint.

Using MEMS technologies, entirely new propulsion system integration schemes may be envisioned, as shown in the right hand side of Fig. 2. These integration schemes may now also include the driver and power conditioning electronics for the individual thruster or valve. Chip-to-chip bonding or integration onto the same chip of various components and the associated driver electronics may lead to extremely compact propulsion modules that in its entirety may now be as small as the tiniest available conventional components to date. These modules will feature minimal external interfaces and could possibly be directly interconnected with the propellant tank. Furthermore, if on-chip power conditioning can be provided, these modules may accept almost any provided microspacecraft bus voltage and be able to convert them internally to the voltages required by the component, thus significantly increasing design flexibility.

Challenges

Propulsion modules such as those discussed above have not yet been realized. However, as illustrated on the right hand side of Fig. 2, chip-based propulsion component and driver electronic development has begun at various laboratories and commercial outfits. System integration issues, such as packaging and thermal considerations for the entire module, will require increased attention as the individual components mature. In addition, there are still technological hurdles to be overcome in the development of

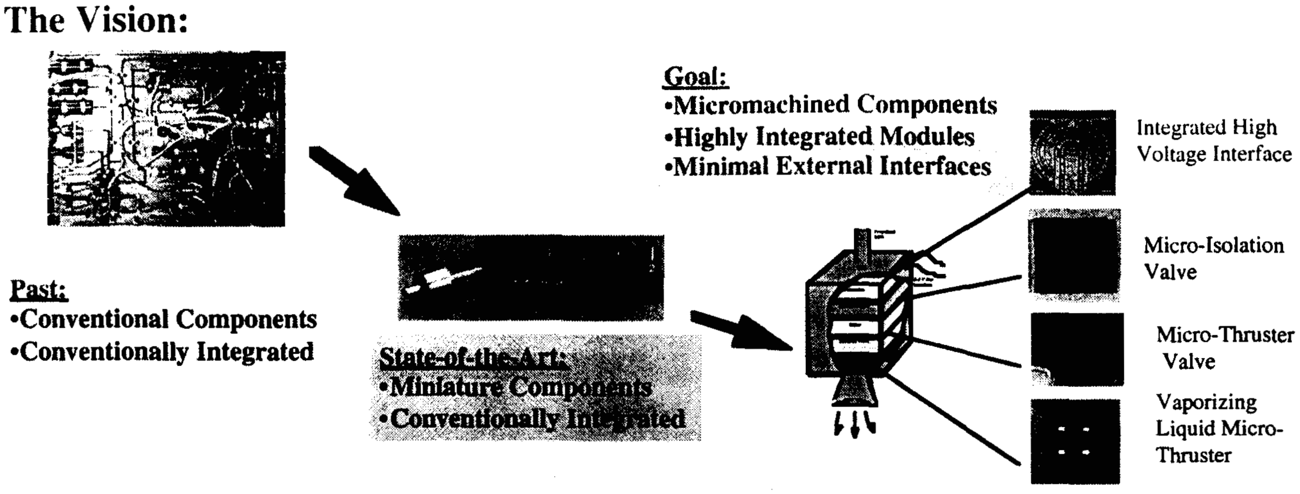


Fig. 2: Proposed Novel Micropropulsion Integration Schemes

the components themselves, some of which are summarized in the following [8].

Scaling -- Scaling issues are of major importance in the development and design of micropropulsion devices. The increased surface-to-volume ratio of either plasma discharge chambers in electric engines or combustion chambers in chemical engines pose challenges as they lead to increased electron wall losses from the plasma, or heat losses from the combusting propellant, respectively, both adversely affecting thruster efficiencies. Viscous flow losses in small diameter nozzles may reduce available specific impulse values. In valve design, the substantially decreased seat dimensions may lead to very tight filtration requirements.

Other propulsion feed system components, such as propellant tanks, may not lend themselves to substantial miniaturization on the MEMS scale at all. Given that the volume of a spherical tank, for example, is proportional to the cube of its diameter, even substantial reductions in propellant mass and, thus, tank volume, have only limited effects on the tank diameter. Tanks may therefore still need to be macro-machined using metal-forming technologies even for very small microspacecraft.

Interfacing/Packaging -- In cases such as the one discussed above, where a metal tank may have to be interfaced with micro-machined propulsion components, but for reasons of packaging delicate micro-machined devices as well, novel interfacing and bonding techniques may need to be explored. Since most microfabrication is performed today using silicon as a base material, metal-to-silicon bonding techniques may be needed to assemble a micropropulsion system. Low temperature Kovar-to-Pyrex bonding technologies (see Section 6 below) may represent such a technology.

Silicon vs. Non-Silicon Fabrication -- Most microfabrication is conducted today using silicon as the base material. Silicon microfabrication in the propulsion field in the propulsion field, however, raises design concerns, and this fabrication approach is thus a subject of ongoing debate in the propulsion field. For example, material compatibility issues may arise between the silicon material and various propellants. One propellant of choice in many attitude control and intermediate delta-v applications is hydrazine. However, hydrazine, if mixed with water and subjected to heat, may act as a silicon etchant [9]. Fortunately, thin-film coating of silicon with nitride, oxide, or various metals is a standard fabrication procedure in MEMS and, provided that perfect, pin-hole free films can be generated, may circumvent these issues.

Silicon also is an excellent heat conductor with a heat conductance value of about 150 W/mK. While this is an advantage in microelectronic circuit fabrication, as this characteristics aides in cooling the chip, it may be detrimental to propulsion applications where heat, as in the case of a thruster, needs to be conserved and constrained to the propellant. Heat losses from the thruster chip would reduce thruster efficiency. Thin film coatings, even using better thermal insulators than silicon, may not be too effective due to the typically very thin layers that may be deposited before internal thin film stresses lead to film delaminations. As will be seen below, using the example of a vaporizing liquid micro-thruster, other design solutions are being explored to reduce these heat losses.

Although featuring high yield strengths, silicon is brittle and internal pressurization of silicon devices, common in propulsion applications, will need to be carefully examined. As will be shown below, recently conducted tests at JPL using a micro-valve fabricated from silicon and Pyrex have lead to burst pressures as high as 3,000 psig in static burst pressure tests and indicate that that design solutions may be found to overcome this concern.

Finally, the aforemnetioned joining between silicon components and meatl components, such as tans, needs to be addressed.

However, despite these design challenges, the investigation of non-silicon based microfabrication schemes still appears worthwhile. The considerable heritage existing in the field of silicon microfabrication, combined with a substantial existing investment in fabrication equipment and facilities dedicated to the microfabrication of silicon, significantly leverages micropropulsion development efforts. The possibility to integrate silicon micro-structures with silicon based electronics may also speak in favor of silicon based micro-propulsion approaches. Future development activities in both areas, silicon-based and non-silicon-based microfabrication, will be required to determine which approach will show greater merit for micropropulsion applications in the end.

The Brief History of MEMS-Micropropulsion

Throughout the remainder of the paper several MEMS-fabricated micropropulsion components currently under development at JPL will be discussed in greater detail. These include a so called Vaporizing Liquid Micro-Thruster (VLM), vaporizing a liquid propellant to produce thrust for microspacecraft attitude control, micro-ion engines to be used for primary microspacecraft propulsion applications, as well as two valve concepts: a one-time actuating micro-isolation valve aimed at sealing propulsion systems prior to their use, and a micro-solenoid valve developed in conjunction with Moog Space Products Division.

These projects merely represent a small fraction of the work that has been ongoing in MEMS micropropulsion. The first MEMS-based propulsion was apparently proposed by Mitterauer in 1991 [10] in the form of a microfabricated Field Emission Electric propulsion (FEEP) thruster concept study based on field emitter array technology. In this thruster concept ions are extracted from a liquid metal propellant column via field emission and subsequently accelerated by means of electrostatic forces. While conventionally machined devices have been built and tested for many years, micromachined versions of FEEP thrusters apparantly have not been realized so far, however.

Shortly thereafter, in 1994, at the Aerospace Corporation, Janson [11] extended the vision for MEMS-based propulsion concepts to other devices as well, such as MEMS-based resistojets and ion propulsion. These activities were part of a more comprehensive study to investigate microspacecraft designs based entirely on MEMS fabrication techniques [11]. Microspacecraft concepts had also been studied at the Jet Propulsion Laboratory (JPL) at this point, primarily by Jones [7,12-17] as well as others [18,19]. As part of this ongoing activity, a study was conducted at JPL in 1995 to investigate the feasibility of microspacecraft concepts with masses between 15 kg and < 1 kg [20,21]. Several MEMS-based propulsion concepts were conceived and proposed in that study, including MEMS-based phase-change thruster concepts using liquid [22-24] and solid propellants [21], as well as microvalves [25-27].

At about the same time, MEMS-based cold gas thruster concepts were conceived and pursued in Europe, in a collaboration between the European Space Agency (ESA) and ACR Electronic Company and Uppsala University in Sweden [28-30], and MEMS-based solid rocket motor array development had been initiated in France at the Laboratoire D'Analyse et d'Architecture Des Systèmes (LAAS) at the Centre National de la Recherche Scientifique (CNRS) under funding by the Centre National d'Etudes Spatiales (CNES) [31,32].

These early activities were soon followed by a flurry of different micropropulsion projects at various private companies, university laboratories and governmental institutions around the world. Private companies pursuing MEMS propulsion include, in the US, TRW [33] and Honeywell [34] studying so called "digital thruster array" concepts consisting of a multitude of microfabricated, single-shot thrusters; Marotta Scientific Controls developing a MEMS-hybrid cold gas thruster and studying MEMS-based flow controllers; Phrasor Scientific [35] investigating MEMS-fabricated colloid thruster concepts; as well as SRI [36] in the US and Centrospazio [37] in Italy investigating micro-FEEP thrusters. Among university laboratories work is currently performed at MIT [38-41], studying micro-nozzle flows, micro-ion engines as well as micro-bipropellant engines (work is also performed at MIT on a miniature Hall thruster, however, this concept is not MEMS-based [42-44]); at the University of Southern California (USC) [45] investigating micro-ion engine concepts and micro-resistojets; and at Princeton University [34] working in collaboration with Honeywell on digital thruster arrays as well as performing high-resolution thrust stand measurements. Government institutions performing MEMS-related propulsion work include the Air Force Research Laboratory (AFRL) [46,47] pursuing projects on micro-resistojets and micro-ion engines, in part in collaboration with USC, as well as (non-MEMS based) work on Micro-Pulsed Plasma Thrusters (PPT); and the NASA Glenn Research Center [41,48], investigating "digital thruster array" concepts as well. In addition, continued work is performed by the aforementioned players, i.e. the Aerospace Corporation [11,49-51], ESA [28-30], the French LAAS/CNRS/CNES team [31,32], and JPL [22-27, 52-54].

The long-term aim of the JPL efforts is to realize the vision of fully integrated micropropulsion module as described above (see Fig. 2) to reduce the overall mass and volume of the propulsion *system*, as well as to ease and decrease the cost of integration by generating modules with minimal external interfaces. MEMS-based propulsion components as well as chip-based driver electronics are crucial to the success of this approach. Below a summary of recently conducted research performed in this area at JPL is given. Work encompasses all critical propulsion components, such as attitude control and primary thrusters, as well as valves. Future activities will also increasingly include work on chip-based driver/power conditioning electronics to be integrated with the aforementioned propulsion components.

3. THE VAPORIZING LIQUID MICRO-THRUSTER (VLM)

Description of Concept

The Vaporizing Liquid Micro-Thruster concept is aimed at serving attitude control functions on microspacecraft [22-24]. Its current configuration is shown in Fig. 3 in an exploded view. A completed chip is shown in Fig. 4. The VLM operates by vaporizing a suitable liquid propellant inside a micro-machined, thin-film deposited heater assembly. Water, ammonia, and hydrazine are currently under consideration as propellants, although in principle any propellant that can be vaporized, and does not exhibit compatibility issues with the materials of construction, may be used.

The thruster chip itself is of a three-laminate construction. Propellant enters the thruster chip assembly through an opening (currently 50 x 50 μm^2 throat) machined into the bottom wafer. It then flows along a channel machined into the center ("cavity") wafer. Heaters deposited onto the top and bottom wafer form two of the channel walls and heat the fluid to vaporization. The propellant vapor exits the chip assembly through a nozzle machined into the top wafer (throat is 50 x 50 μm^2 also). This nozzle is anisotropically etched into the silicon wafer and thus features a pyramidic "square" shape [22]. This nozzle design serves as a place-holder for more optimized nozzle contours [39,40] to be integrated into future design iterations of the VLM chip.

The heater strips and contact pads are made of gold. A gold layer is also deposited onto the bond surfaces of the top, center and bottom wafers (electrically insulated from the heater strips) to act as a bond medium. A thermal gold compression bonding technique is used to fuse the wafer stack together. The flow channels are formed using a deep trench Reactive Ion Etching (RIE) technique. Recesses anisotropically etched into outside surfaces of the top and bottom wafers reduce the silicon thickness immediately below the heater strips and thus create "thermal chokes", aimed at reducing heat flux from the heaters into the remainder of the chip structure.

Current chip sizes are about 0.9 x 1.5 x 0.1 cm^3. Fabrication of a smaller version (1 x 1 x 0.1 cm^3) has recently been completed and these chips are currently undergoing packaging procedures (see Fig. 5).

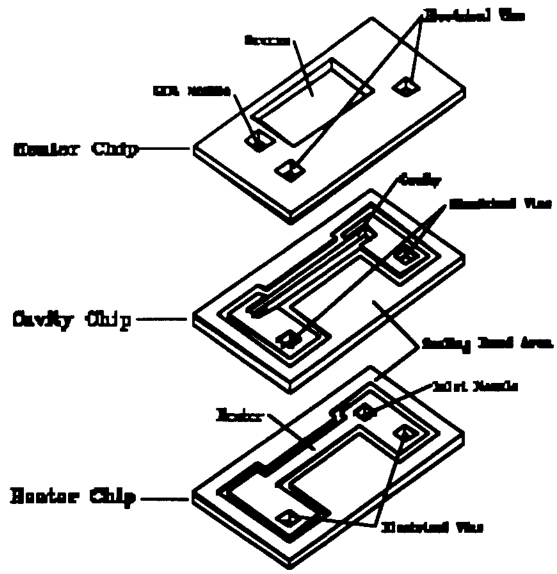


Fig. 3: VLM Design Components (Exploded View)

Fig. 3: First Generation VLM Design

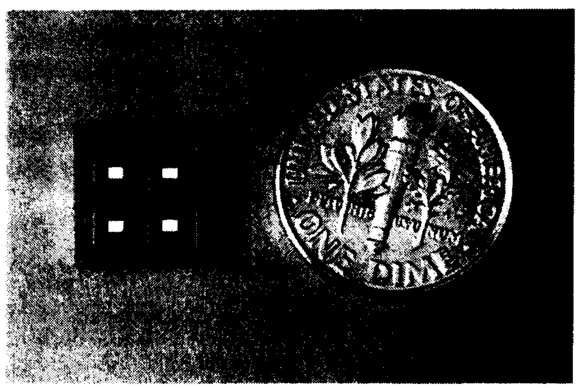


Fig. 3: Second Generation VLM Chip

Applications and Benefits of Concept

The VLM thruster is envisioned to be used as an attitude control thruster on microspacecraft. The benefits of the VLM are its small size and weight (weighing but a few grams), its scalability to potentially very low thrust and impulse bit values (by tailoring the nozzle throat accordingly), its amenability to on-chip integration schemes (compare with Fig. 2) and the use of a liquid propellant.

Small size and weight of a microspacecraft attitude control thruster are of importance since typically three-axis control of a spacecraft may require up to a dozen thrusters.

Any weight savings obtained for a single component thus multiplies accordingly. Even larger weight savings and reductions in system complexity can be achieved if these thruster components are directly integrated with other feed system and celectronic components into tightly configured, compact propulsion modules by chip-to-chip bonding (see above). The chip-based VLM design lends itself to such integration schemes.

Very low impulse bits on the order of µNs may be required for very small microspacecraft for accurate pointing depending on required pointing accuracy. Scalability to such small impulse bits will thus greatly increase the application potential of this technology to very small craft.

Liquid and solid propellants can be stored much more compactly and in lighter-weight tanks than gases. In addition, propellant leakage concerns for a liquid are much reduced over a gas stored at high tank pressures. This is of particular importance for microspacecraft applications where onboard propellant supplies may be extremely limited due to the size of the craft.

Current Status of Development

A set of VLM chips of the design shown in Figs 3 and 4 has recently undergone proof-of-concept testing. Using water propellant, on-chip vaporization could be demonstrated in a simple bench-top experiment (see Fig. 6). Water was pressure-fed from a tank through a filter and solenoid valve into the thruster. Power levels at which onset of vaporization was observed for various feed pressures and flow channel designs are shown in Fig. 7. A description of the various channel geometries tested is given in Table 2. Chips were mounted into a chip carrier, as shown in Fig. 6, and the chip carrier was epoxy bonded to an aluminum or Vespel nut by means of which the VLM assembly could be

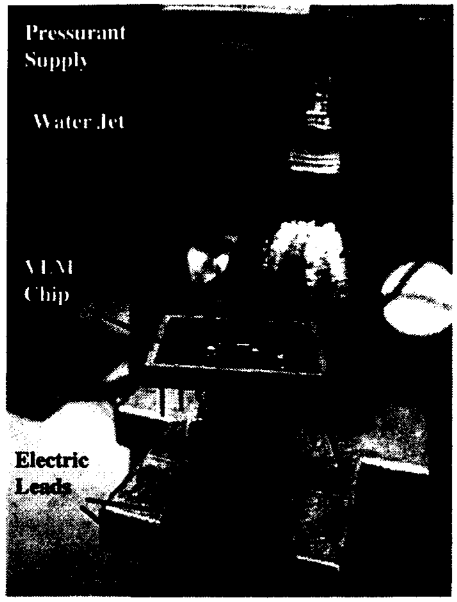


Fig. 6: VLM Bench-Top Test Rig

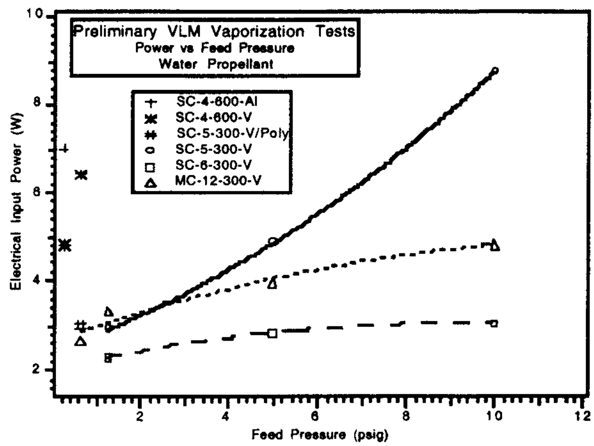


Fig. 7: VLM Power Requirements vs. Fee Pressure

Table 2: VLM Chip Test Articles

Designation	Heater Length (mm)	Channel Cross Section (μm^2)	Channel Type	Fixture Material
SC-4-600-Al	4	950 x 600	Straight	Aluminum
SC-4-600-V	4	950 x 600	Straight	Vespel
SC-5-300-V	5	950 x 300	Straight	Vespel
SC-5-300-V/Poly*	5 (PolySi)	950 x 300	Straight	Vespel
SC-6-300-V	6	950 x 300	Straight	Vespel
MC-12--300-V	12.16	400 x 300	Meandering	Vespel

*featuring a heater made from polysilicon. All other heaters made from gold.

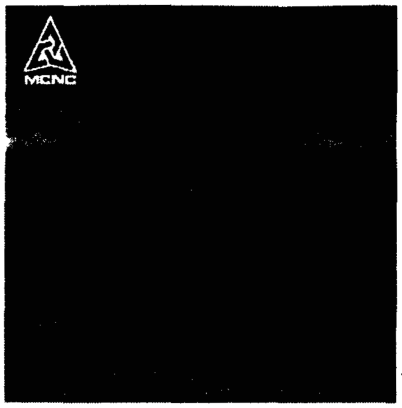


Fig. 9: Field Emitter Tip (Courtesy MCNC)

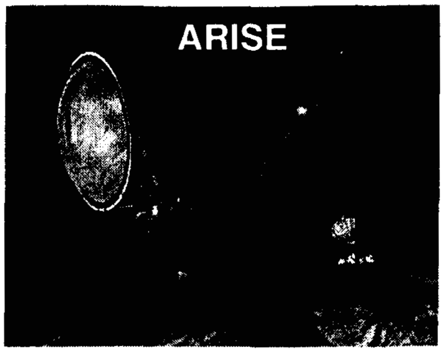


Fig. 10: Conceptual Setch of ARISE Inflatable Spacecraft Mission

FEA arrays have been fabricated for flat panel display applications, however, in that application operate under much more benign presure conditions of about 10^{-7} Torr as opposed to background pressures expected to be as high as 10^{-3} Torr in micro-ion engine discharge chambers, or on the order of 10^{-5} Torr in ion engine plumes. These higher background pressures pose lifetime concerns as positively charged ions from the discharge or plume plasmas may erode the negatively biased FEA tips, significantly reducing the extracted current for a given voltage. Sputter resistant carbide tip structures, carbide and nitride coated silicon tip structures, as well as planar carbon field emitters are therefore being considered for this application. These technologies are discussed in greater detail in a companion paper [55].

Applications and Benefits of Concept

Micro-ion thruster concepts and component technologies have been proposed for use as primary propulsion devices for micro-spacecraft. Due to their potential to deliver high specific impulses (about 3,000 sec), propellant consumption to achieve a given delta-v requirement is much lower than for chemical thrusters (max. specific impulse for earth-storable bi-propellant engines is about 300+ sec). Reduced propellant requirements will keep overall spacecraft mass and volume low, provided that sufficient power can be provided to operate the ion engine (about 50 W estimated).

Micro-ion thrusters may also find applications on larger scale spacecraft for attitude control purposes. For example, large inflatable spacecraft (see Fig. 10) depending on their mass distribution may be subject to solar disturbance torques. Mounting micro-ion thrusters onto the inflatable structure, and taking advantage of the potentially large moment arm of such a location, could significantly reduce thrust levels and propellant cosumption required for solar disturbance torque compensation. Since solar disturbance torques will act continuously, a low-thrust, high specific impulse, long-lifetime, continuously operating thruster will be required. Ion engines, due to their suitable engine characteristics in this regard, appear to be well suited for such a task. However, integration of thrusters onto an inflatable structure requires these devcies to be very small, compact and light-weight.

Ion engines typically operate on inert gases, such as xenon or possibly krypton. These propellants do not pose any contamination concerns, unlike liquid metal propellants used in other electric micro-thrusters, such as FEEPs. Micro-ion engines may therefore be used in applications where sensitive optical surfaces on a spacecraft are exposed. This is of increasing importance for microspacecraft, since these craft, as alluded to in the Introduction, may be used in constellations. Situations may arise where thrusters operating on one spacecraft may fire into the direction of another spacecraft, therefore creating increased contamination concerns due to "inter-spacecraft" contamination.

Current Status of Development

Development of a micro-ion engine is the most complex tasks of all JPL micropropulsion efforts currently undertaken. On the one hand, this is due to the need to miniaturize several key subsystems, such as cathodes/neutralizers and grids, each representing a major development task in its own right. On the other hand concerns related to the efficient operation of micro-gas discharges loom large. For example, using permanent magnets to lengthen electron paths inside the discharge chamber to increase engine efficiency, as is commonly practiced in conventional ion engines, is not a likely option for micro-ion engines due to the potentially prohibitive weight penalty. New chamber geometries may very well have to be explored [45].

Among the key component technologies currently being studied intensely are FEAs. A detailed description of these experiments may be found in a companion paper [55]. Different FEA types, featuring different geometries and cathode materials, are currently being investigated. These include molybdenum and silicon tip cathodes, however, both designs showed signs of severe erosion as background pressure levels were raised to about 10^{-5} Torr. On the other hand, FEAs using carbon film cathode material appear to be plumbed into the test rig. Due to the lower heat conductivity of Vespel versus aluminum, the chips packaged using Vespel nuts lead to much lower power requirements. Power levels as low as 2 W have been recorded. Required operating voltages at those power levels were close to 2 V.

The channel height was found to have a pronounced effect on vaporization. Channel heights of 600 µm lead to poor vaporization with frequent liquid droplet emission, and high power requirements of 7 W even for extremely low feed pressures of less than 1 psi. Reducing the channel height to 300 µm dramatically improved the quality of vaporization with no liquid droplet emission observed above a certain power level. These power levels were much reduced over those found for the 600 µm tall channels, ranging, as mentioned, as low as 2 W.

It should be noted the data obtained so far is very preliminary and demonstrates the early development stage of this concept. The value of the data obtained so far primarily lies in the proof of concept of the VLM approach. No quantitative comparison between the various chip configuration can be drawn yet as flow measurements of the very low flow rates passing through the VLM were not yet possible, pending the availability of suitable flow meter technology. A set of chip-based mass flow meters provided by a commercial vendor is currently under investigation. However, chips tested so far were unable to resolve the mass flow rates (< 200 µl/hr under vaporizing conditions in atmosphere). Flow meter chips rated for smaller flow rates are currently being assembled.

Furthermore, recent tests have only been performed under atmospheric conditions and need to be repeated under vacuum. At that point, thrust stand and - in conjunction with mass flow measurements - specific impulse measurements will need to be performed. New chips are also being fabricated aimed at reducing heat losses into the chip structure. More efficient chips would allow higher mass flow rates to be vaporized at power levels comparable to those mentioned above. To this end, the chip foot-print has been reduced by 30% and the recess opposite the heater strips has been deepened using an RIE etch, aimed at improving the thermal choke and reducing conductive heat losses. A VLM chip set based on the design is shown in Fig. 5 and is currently being packaged to undergo testing in the near future. VLM chip configurations providing even higher thermal resistances to further reduce conductive losses through the geometry of their design are currently in the design stage.

4. MICRO-ION THRUSTER

Description of Concept

Micro-ion engine concepts are being proposed for microspacecraft primary propulsion applications. A micro-ion thruster is a miniaturized version of a conventional ion engine in which a low pressure gas discharge is being created through bombardment by electrons generated by a cathode. Ions are extracted form the gas discharge and electrostatically accelerated to high velocities (about 30,000 m/s) in a set of accelerator grids, requiring the application of voltages of about 1 kV between the grids. The extracted (positively charged) ion beam has to be neutralized by an externally mounted cathode (neutralizer) providing electrons to be injected into the beam.

Currently, a 1-3 cm dia. MEMS-hybrid micro-ion engine (see Fig. 8) is being envisioned by JPL for microspacecraft as well as certain larger scale spacecraft applications (see below). Entirely MEMS-machined ion engines do not appear practical due to increased electron wall losses from the discharge in small (high surface-to-volume ratio) discharge chambers, leading to efficiency losses [38]. Given the larger required dimensions for the discharge chamber, this component may therefore be machined using non-MEMS fabrication methods. However, the engine will feature MEMS components, such as field emitter arrays (FEAs) to serve as engine cathodes (providing electrons to ionize the propellant) and neutralizers (to neutralize the ion beam and avoid spacecraft charging). Other ion engine components for which MEMS approaches are being contemplated are the accelerator grids (to extract and electrostatically accelerate ions from the engine discharge), feed system components (valves, flow meters and controllers) as well as the power conditioning system.

FEAs are a key technology required for the success of a micro-ion engine system. Hollow cathodes typically used in conventional ion engine designs are too large, heavy, complex and power consuming to be used for engines as small as 1- 3 cm dia. Field emitters consist of gated tip structures as shown in Fig. 9. By biasing the tip negatively with respect to the gate (recognizable in Fig. 9 as the lighter colored planar structure creating an over-hang over the aperture surrounding the tip), field emission leads to electron emission from the tip if a sufficient voltage is applied between gate and tip, depending on tip/gate separation. Gate voltages of less than 40 V are being targeted for field emitter apertures of about 0.2 µm. The field emission process requires no heating and power consumption is thus low, limited to losses incurred through gate impingement currents.

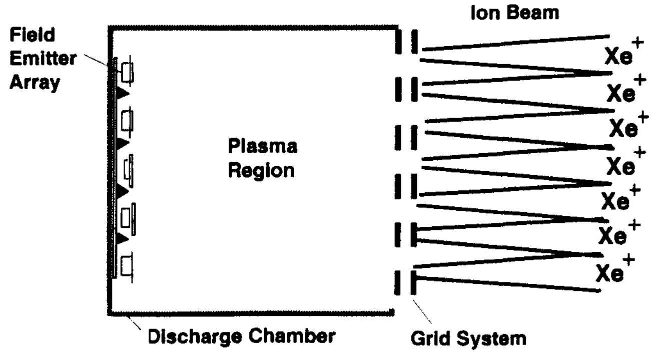


Fig. 8: MEMS-Hybrid Micro-Ion Engine Concept

very robust, however, available cathodes featured large cathode-gate gap distances and consequently require very high voltages. The testing of carbon film cathodes with microfabricated gate structures is currently being prepared, reducing tip-gate seperations and in turn reducing operating voltages to more suitable levels. In addition, the fabrication of tip-structured FEA arrays featuring carbide tips or carbide coated is being prepared. These structures are envisioned to be integrated with microfabricated, integrated repeller grids (Cathode Lens and Ion Repeller - CLAIR [55], see Fig. 11). These grids would serve to repel ions from the engine or plume plasma which otherwise may have impacted on the tip structures to cause sputter erosion. Test fabrication runs for CLAIR structures has begun, aimed at overcoming the challenge associated with the thin-film deposition of multiple (up to six) films stacked on top of each other needed to form the various electrodes. A more detailed review of ongoing research in this area may be found in Ref. [55].

Micro-ion engine accelerator grid technologies have also been a focus of investigation. MEMS-microfabricated grid structures have been contemplated. The reason for pursuing such an approach may be found in the fact that smaller diameter engines allow grids to be spaced much more closely with respect to each other since the amount of electrostatic-stress induced grid deformation will be less. Placing grids closer with respect to each other will increase the grid perveance, proportional to $1/d^2$, with d being the grid spacing. Thus, higher beam currents could be extracted from the engine for a given voltage, provided that sufficiently large ionization fractions can be provided in the ion engine plasma. However, ion optical considerations generally require grid aperture diameters to be scaled down in size with the grid spacing in order to avoid ion impingement on grids causing potentially engine life threatening grid erosion. Smaller aperture diameters, and the requirement to place apertures of the various grids (screen, accelerator, and, potentially, decelerator) of a grid system concentrically with respect to each other, requires tight machining tolerances. Current, "macro-machined" grids are fabricated within 0.05 mm, or 50 μm tolerances, representing a limit in most cases for many conventional machining techniques, such as

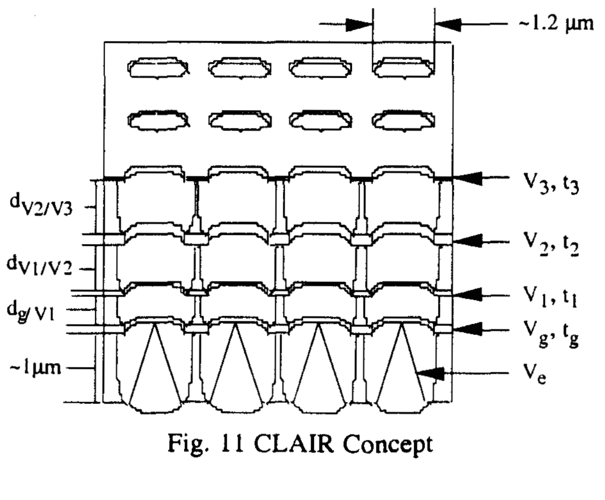


Fig. 11 CLAIR Concept

electric discharge machining (EDM) or laser drilling for example. Using microfabrication techniques, however, much smaller tolerances can easily be obtained. In addition, the ability to produce entire batch-fabricated grid systems, not requiring any additional assembly and grid alignment procedures, weighs in favor of microfabrication approaches as well.

Microfabricated grids will differ from macro-scale grids by the insulator layer required to be left in place between a grid pair (see Fig. 12). This insulator layer is needed to support the very thin grid electrodes, likely being not much thicker than 1 μm, possibly considerably less. The advantage of this technique would be that electrostatic grid deformation would be counteracted by the insulation layer. Disadvantages are that (1) electrostaic breakdown may occur through the insulator layer, as well as along free insulator layer surfaces, such as grid aperture wall surfaces; and, (2) conductive material sputter-eroded from the grids or other engine surfaces may deposit itself along insulator wall surfaces and thus short the grids.

Microfabricated, fully integrated shadow-shielding has been contemplated to protect these surfaces and possible design solutions have been discussed. Before fabrication of such a complex microfabricated structure is undertaken, however, experiments aimed at studying the electrostatic insulator breakdown are in order to study the sensibility of such an approach. Silicon dioxide is a typical insulator material used in microfabrication and was therefore used as the test material. The particular oxide chosen was Low Temperature Oxide (LTO), deposited in a chemical vapor deposition (CVD) process. Reasons for this choice were the relatively large insulator thickness that can be obtained with this material, up to about 5 μm. As will be seen below, other oxides can only be deposited or grown to much smaller thicknesses.

The larger obtainable oxide thickness was of particular interest in the context of its intended application. However, no breakdown test data for large oxide thicknesses be found in the literature, although an ample supply of data existed for sub-micron thicnesses. Therefore grid test chips were fabricated to measure breakdown electric filed strengths at various oxide thicknesses and environmental temperatures (see Fig. 13). Figure 14 shows the schematic of two test

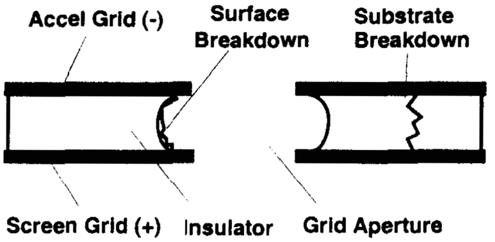


Fig. 12: Anticipated Grid Breakdown Modes

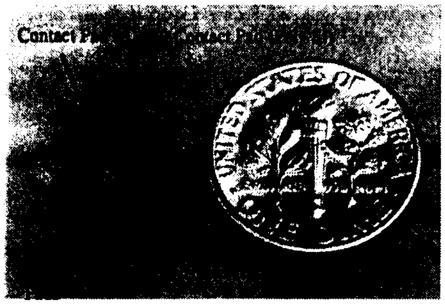
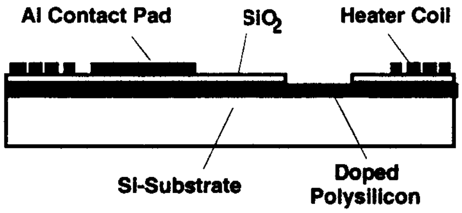
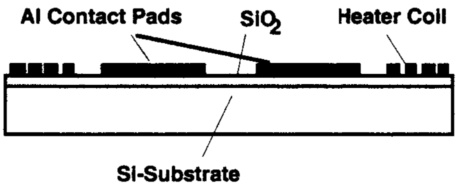


Fig.13: Grid Breakdown Test Chip



(a) Substrate



(b) Surface

Fig. 14: Grid Breakdown Test Chip Schematics

chip types. Figure 14 (a) shows the design of a chip aimed at studying breakdown through the bulk material (substrate breakdown) and Fig. 14 (b) shows a chip design aimed at studying surface breakdown. Both chips are based on a silicon substrate wafer. In the case of the substrate breakdown chip a conductive doped polysilicon electrode is deposited first, followed by the deposition of the oxide layer to be investigated. An aluminum metal pad serves as the second electrode. An aluminum heater coil is also deposited onto the chip to allow for testing of the chip at temperature values higher than ambient.

The surface breakdown chip does not feature the doped polysilicon layer, rather, the second electrode is another aluminum patch placed on top of the oxide layer separated from the first patch by a specific distance over which the voltage is to be applied. Both types of chips were placed onto probe stations were they could be electrically contacted (see Fig. 15). Surface breakdown tests were performed under vacuum conditions (typically 3 x 10^{-5} Torr), while substrate breakdown test could be performed under atmospheric conditions, simplifying the test procedure. A more detailed description of the experiment is given in Ref. [52].

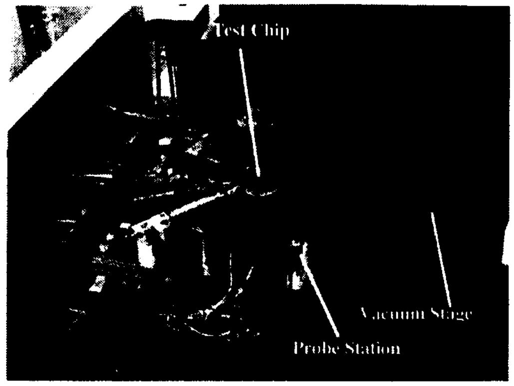


Fig. 15: Probe Station Set-Up

Results obtained with substrate breakdown tests were encouraging. Figure 16 shows test results (open symbols) compared with test results obtained in other studies using different oxides (solid symbols) [52]. As can be seen, a dramatic increase in voltage stand-off capability over other oxides can be observed, largely attributed to the thicker oxide layer than can be deposited using the LTO-CVD process [52]. Breakdown electric field strengths ranged around 600-700 V/μm, only slightly decreasing with higher temperatures up to 400 C [52]. For the maximum oxide thickness tested (4 μm) this translates into a stand-off voltage of roughly 3 kV. These breakdown values are far higher than required for successful grid operation.

Unfortunately, surface breakdown field strengths were found to be much lower. The breakdown field strengths varied largely with the electrode gap, increasing as the gap decreased (see Fig. 17). At a gap of 5 μm, roughly corresponding to the maximum obtainable LTO oxide thickness, breakdown field strengths as high as 200 V/μm were measures, representing a voltage stand-off capability of merely 1 kV. This performance is rather marginal for grid operation.

Ion engine grid systems may therefore represent a propulsion component were MEMS technology may not be a suitable candidate for fabrication. Although the option of studying the breakdown characteristics of even thicker,

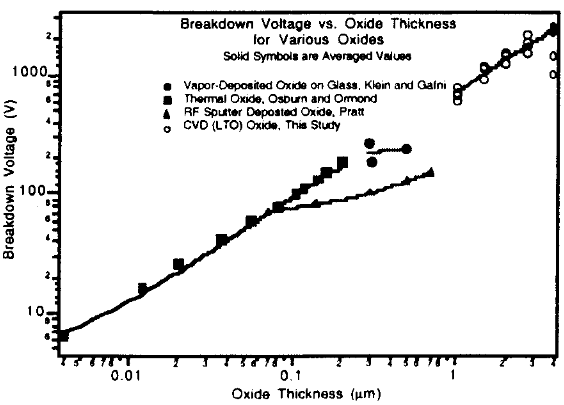


Fig. 16: Breakdown Voltages vs. Oxide Thickness for Various Oxides

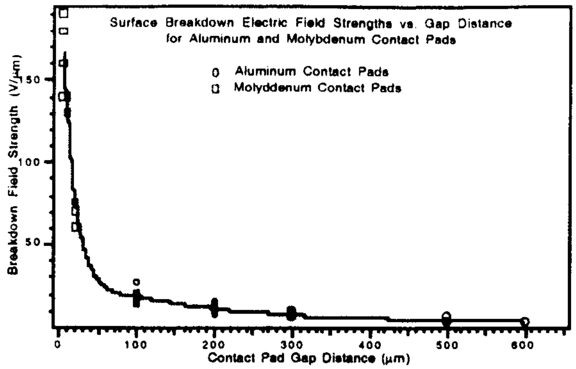


Fig. 17: Surface Breakdown Field Strengths vs. Gap Distance

Plasma-Enhanced CVD (PECVD) oxides exists, non-MEMS based miniature grid fabrication schemes based on chemical etching procedures will be investigated as well.

In addition to component development work in the cathode and grid area, numerical modeling of micro-ion engine discharge plasmas is being performed. These modeling effort will be performed jointly with the Air Force Research Laboratory (AFRL) at Edwards AFB. AFRL will conduct neutral flow modeling using a Direct Simulation Monte Carlo (DSMC) code. Data obtained with this code will serve as inputs to a JPL provided Particle-in-Cell (PIC) code simulating charged particle flows. Results obtained will shed light on micro-ion engine design and the minimum engine diameters that realistically may be obtained. These efforts, combined with the component development activities detailed above, will then culminate in the building of a micro-ion test engine.

5. THE MICRO-ISOLATION VALVE (MIV)

Description of Concept

The Micro-Isolation Valve (MIV) is a normally-closed one-time actuation valve designed to seal propulsion feed systems prior to their use, providing zero leak rates [25-27]. A schematic of the isolation valve chip can be seen in Fig. 18. The micro-isolation valve in its current form is a micromachined, silicon-based device that relies on the principle of melting a silicon plug, possibly doped to enhance its electrical conductance, blocking the valve flow passage in the normally-close position. A close-up of the channel passage and the sealing plug can be seen in Fig. 19. The plug is etched in place. Melting of the plug will open the valve and will be achieved by passing an electric current through the plug and resistively heating it. The valve will thus serve a similar function as a normally-closed pyrovalve, providing an essentially zero leak rate prior to actuation by completely sealing the flow passage. Unlike a pyrovalve, however, the here proposed valve will not rely on pyrotechnic actuation, thus avoiding the potential for pyroshocks as well as alowing for valve integration with other MEMS-based components (compare with Fig. 2).

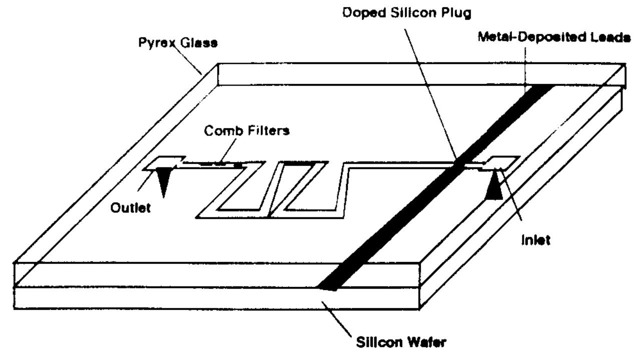


Fig. 18: Schematic of the Micro-Isolation Valve Concept

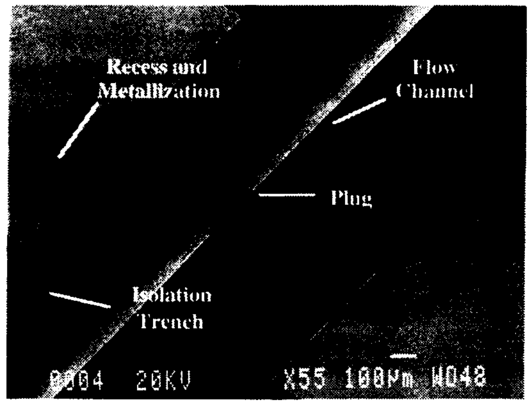


Fig. 19: Close-Up of Plug Area

The MIV consists of two basic components: the silicon chip featuring all the flow passages and valve inlet and outlet, and a Pyrex cover to seal the flow passages while allowing a view of the internal design of the chip for experimental evaluation of the concept. Later versions may be entirely assembled from silicon. The silicon-Pyrex bond is achieved by means of anodic bonding, a standard bonding technique in the microfabrication field [25,27]. Channels in the chip are fabricated using deep trench reactive ion etching (RIE). This etching process is highly an-isotropic and allows deep features to be etched into the chip with very straight wall sections up to aspect ratios as high as 30:1. Metal (gold) leads deposited onto the silicon substrate, partially overlapping the doped-silicon plug region, will connect the plug to an external valve-opening circuitry.

In order to prevent plug debris from contaminating flow components located downstream of the isolation valve, it is crucial to trap the debris within designated, non-critical regions of the valve without re-closing the flow path again. It is being speculated that due to melting rather than cold fracture of the plug debris count may be reduced and fewer, larger debris particles may be produced, which will be easier to trap. Nonetheless, filtration and other debris trapping schemes will be required. Evidence of condensation of molten plug debris on downstream channel walls has been observed (see below) and may be exploited by placing bends into the downstream flow channel to condense debris in its (widened) corners. A comb filter integrated in the flow path will serve to trap debris that may not have been condensed at the flow path walls, but instead have solidified in the propellant stream. Using MEMS-based techniques, it is expected that very small filter ratings may be produced, wel into the μm-range. An assembled MIV chip can be seen in Fig. 20. Chip size is approximately 1 x 1 x 0.1 cm^3.

Applications and Benefits of Concept

Isolation valves, such as the commonly used pyro-valves used in conventional feed systems, are one-time opening valves (normally closed type) or one-time closing valves (normally open type). Thus, they cannot replace the function of a valve allowing for repeated actuation, but serve critical functions in a propulsion system nonetheless. Isolation valves serve to seal the propulsion system during launch, for example, where valves designed for repeated actuation may shutter, leading to leakage, or seal a propulsion system during long, inactive interplanetary cruises, providing zero leak rates. The latter case is of increasing relevance for microspacecraft applications. Here, microspacecraft may be used in mission scenarios where these craft are attached to larger spacecraft to serve as probes in order to perform more risky portions of a mission. For example, in the case of the aforementioned Saturn ring explorer scenario [5], microspacecraft may only be activated just pior to release from the larger cruise stage. The MIV valve would help conserve propellant in the preceding, very long duration dormant phase of the microspacecraft.

Apart from providing zero leak rates prior to activation, other benefits of the MIV concept are the fact that no pyrotechnic actuation is required, unlike for conventional pyrovalves, thus reducing structural loads on other microspacecraft components, the much smaller size and weight (a few grams) of the MIV valve when compared with conventional pyrovalves (approximately 150 grams in weight), and its amenability to on-chip integration schemes as discussed above (compare with Fig. 2).

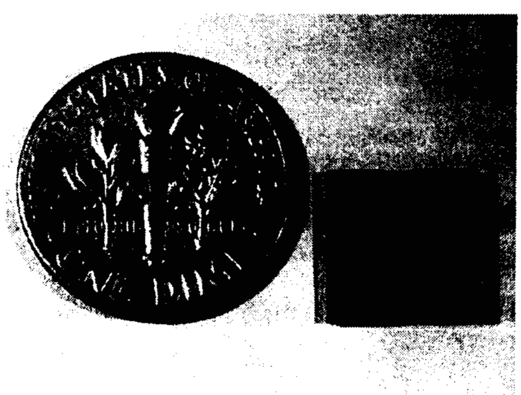


Fig. 20: Micro-Isolation Valve Test Chip

Current Status of Development

The MIV valve faces three key feasibility issues. First, successful melting of the plug within power/energy levels acceptable for microspacecraft needed to be proven. Second, since an isolation valve will see the full tank pressure, it will have to be able to sustain potentially high internal pressures. If used in a cold gas application, such as ion engine feed systems, these pressures may be as high as 2,000 psi, and even higher pressures may be encountered in a conventional cold gas system. Thirdly, all debris generated by the valve in the plug removal process needs to be contained within the valve to prevent potential downstream contamination of other flow components.

The first two feasibility issues were addressed successfully in the past program, and promising initial observations were made regarding the debris trapping ability of the valve. Plug melting tests showed that the valve could be opened with as little as 16 mJ of stored energy within 0.1 ms depending on plug thickness [26]. The aforementioned data were obtained with a 25 μm plug. Results of such a plug melting test are shown in Fig. 21. Interesting to note is that molten plug debris has condensed on the channel walls, a fact that will be exploited in future debris trapping schemes. Power traces for two valves are shown in Fig. 22.

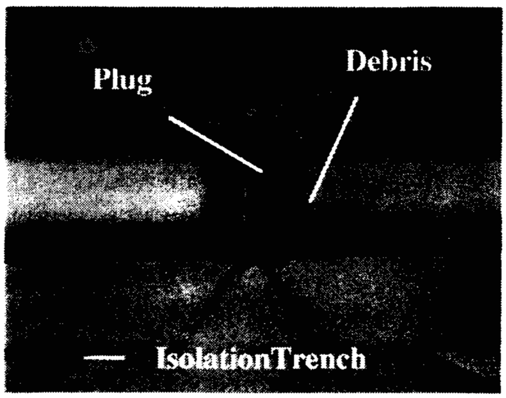


Fig. 21: Plug Region after Valve Firing

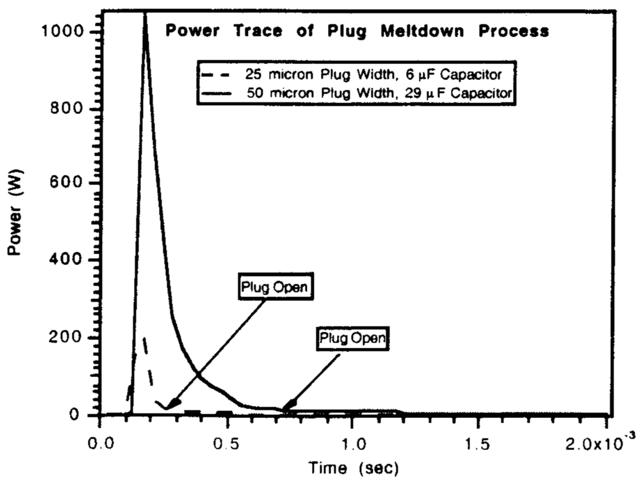


Fig. 22: Power Trace to Open Valve

Note that even though power levels peak at about 1 kW for the valve with a 50 µm plug, total energy levels required to open the valve even in this case of a thicker plug are only 0.1 J. These values appear reasonable and within design limits for microspacecraft.

Isolation valve burst tests were performed as well and resulted in burst pressures as high as 3,000 psig depending on plug thickness (see Fig. 23) [25,26]. Note that these high burst pressure values were obtained with a valve chip consisting of a silicon/Pyrex laminate, pointing to the extraordinary toughness that can be obtained with properly designed MEMS devices. However, these test results were obtained in static, ambient temperature tests only. No thermal cycling or vibration was performed prior to the test.

Note that two failure modes were observed for valve burst [26]. Up to about 20 µm plug thickness, the failure mode is plug rupture. Above about 20 µm plug thickness the failure mode is Pyrex failure. In these cases the Pyrex fails just above the chip inlet (see Fig. 24). Obviously, this problem can be corrected by using thicker Pyrex material, or, in later tests, other non-transparent materials that may be tougher, such as silicon for example. Therefore, it appears feasible to reach even higher burst pressure values than the ones documented here.

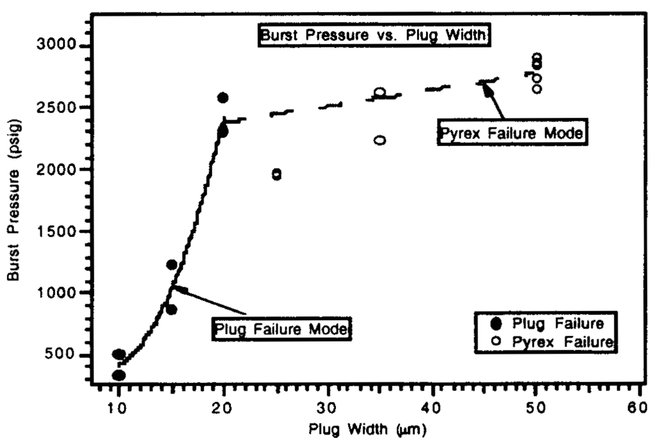


Fig. 23: Burst Pressure vs. Plug Width

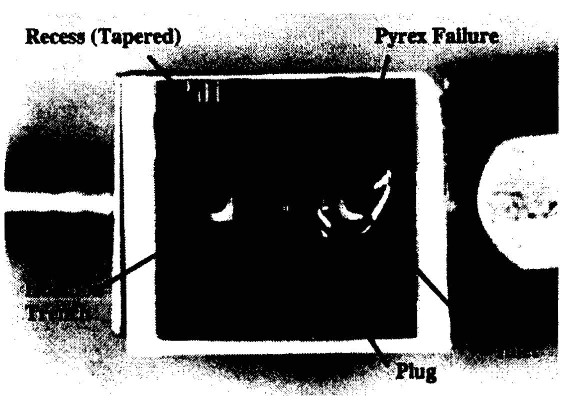


Fig. 24: Post-Burst Test Image of MIV

6. MICRO-SOLENOID VALVE

Description of Concept

Work on a micro-solenoid valve was recently initiated in collaboration between Moog Space Products, Inc. and JPL. This valve, also termed the Moog Micro-Valve (MMV), is a hybrid metal/MEMS construction and approximately 1 cm^3 in size. The valve body is machined using low cost metal batch fabrication methods while the coil is MEMS-fabricated. The valve is designed to be interfaced directly through low temperature Kovar-to-Pyrex bonding with other MEMS devices, such as the above described MIV valve or VLM thruster, providing potentially very compact micropropulsion modules (see Fig. 25).

Applications and Benefits of Concept

The proposed MMV valve can be used in any number of micropropulsion feed system applications, as well as in low-flow macroscopic feed systems, such as electric propulsion feed systems. There also exists a substantial commercial, non-space market for such a valve, covering such varied areas as micro-instruments, micro-fluidics, bio-chemical applications, and micro-robotics. With respect to micropropulsion applications, the MMV concept will be characterized by faster actuation times, higher sealing forces, and a larger thermal operating range than previous silicon MEMS-based microvalves [56].

Compared with more conventional valve technology, this valve, through the use of batch-fabrication processes in the metal body as well as coil fabrication, can be produced more cost-effectively and is potentially scalable to much smaller sizes. While wire-wound coil technology may have reached a limit with respect to the degree of miniaturization obtainable, the MEMS-based coil technology may still have a significant potential to be miniaturized even further. The potential to interface this valve directly with MEMS-based components, rather than relying on complex micro-tube joints, may allow for extremely small propulsion modules to be realized, thus providing a keystone element in the realization of the vision indicated in Fig. 2.

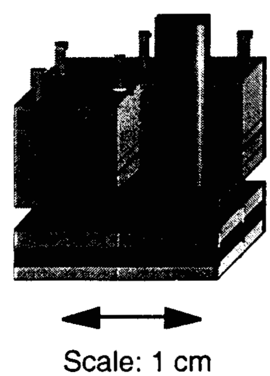


Fig. 25: Micropropulsion Module

Current Status of Development

This MMV valve work is in its earliest development stages and has only recently (Summer 1999) been initiated. Currently, design layouts for the valve are complete and critical experiments in key technology areas (low temperature Kovar-to-Pyrex bonding, MEMS coil fabrication) have begun. An example of a micro-coil fabrication test run is shown in Fig. 26, showing a spiral shaped coil pre-form. More detailed results will be reported in the near future as this project develops.

7. CONCLUSIONS

MEMS micropropulsion efforts may lead to highly integrated micropropulsion modules and systems which may provide the potential for significant further miniaturization even over today's smallest feed system components. These microfabricated micro-propulsion modules may even include the necessary driver and power conditioning electronics, and thus provide highly integrated propulsion systems with minimal external interfaces. Advantages of such an approach would not only be significant mass and volume savings over more conventional architectures, but also reduced cost and complexity of propulsion system integration into a microspacecraft bus.

Several projects conducted at JPL to this end were reviewed, as well as work performed on other projects in this field by other institutions. Key areas of activity at JPL currently encompass all critical propulsion system areas, such as attitude and primary propulsion, valves, and increasingly in the future, chip-based driver electronics.

Critical milestones in evaluating the feasibility of several of the propulsion components investigated could be achieved. A vaporizing liquid micro-thruster was shown to be able to function at power levels as low as 2 W. A micro-isolation valve could be activated and opened with required energy levels as little as 16 mJ. Work on critical ion engine technologies, such as field emitter arrays and micro-grids, has given new insight into the design issues to be addressed and lead to new design approaches. Most recently, an industry collaboration between Moog Space Products Division and JPL could be initiated to develop a novel micro-solenoid valve, aimed at circumventing limitations of previous wire-wound coil designs to achieve even higher degrees of miniaturization, reduced cost of fabrication, and increase levels of integration with other micropropulsion components.

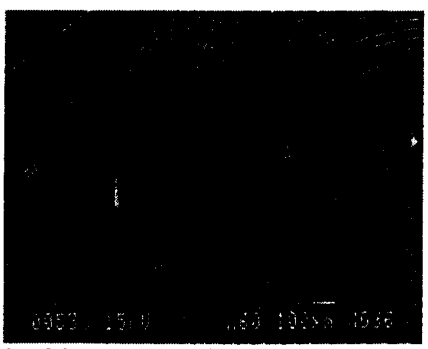


Fig. 26: MEMS Coil Fabrication

Despite recent achievements, many design challenges still remain to be overcome, requiring new diagnostics to characterize the quantitative performance of micropropulsion devices, such as engine thrusts and impulse bits, specific impulses as well as mass flow rates, likely resulting in further design changes to improve the devices. Propellant compatibility issues will need to be studied. In the micro-ion engine activity, scaling issues need to be further investigated and FEA technology still requires substantial advances. Debris trapping schemes need to be explored for the micro-isolation valve. A first prototype of the micro-solenoid valve is expected to be completed in the Spring of 2000.

However, if successful, these technologies, as well as related others, could potentially lead to substantial further reductions in size an mass and much higher degrees of integration for micropropulsion systems, thus creating entirely new design solutions for microspacecraft.

8. ACKNOWLEDGEMENTS

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